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A review on light-emitting diode based automotive headlamps

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ABSTRACT

Benefited from the fruitful results of general light-emitting diode (LED) lighting, the LED is utilized in the automotive forward lighting recently, the LED headlamp, due to its ability of improving the efficiency, durability and comfort of the automobile. Both the rough operating environments and rigorous safety standards make the design and verification of the LED headlamp face more challenges than that of the general LED lighting. Although there are some concerns about the status of the LED headlamp, these efforts mostly focused on a single issue, and little knowledge has been established from a system-level aspect. To obtain an up-to-date and systematical summary of the progress of the LED headlamp, in this review, after a description of the fundamentals of the LED headlamp, its design methods are scanned firstly following the categorized components: the LED array module, the heat management, optics control as well as the driver electronics; then, the verifications of the LED headlamp are explored according to the plug-in efficiency, cost, lifetime and reliability; next, the trends of the LED headlamp with the additional function of data transmission and integration of human factors are illustrated; and a conclusion is given finally. The results show that the LED headlamp is a complex electrical–optical–thermal–mechanical system, involved human factors; currently it reaches the state-of-the-art on the efficiency, while the cost is about 350% more than that of the halogen headlamps; additionally, the lifetime and reliability issues, which are closely related with the junction temperature and the moisture diffusion, least understands in human response to LED light as well as immature regulations do challenge the development of LED headlamp. However, the system-level, functional and human factors based solutions cast a light on the future LED headlamp.

Contents

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1. Introduction

The headlamp is a lamp attached to the front of an automobile to provide the driver the visual range while overcome the light glare of oncoming vehicle when driving at night or in obscured light conditions. The headlamp is typically considered as one of the most important safety devices on automobiles. It is reported that about 40% of fatal accidents is happened during night, and declared that the diminished visual performance is the major contributor [1,2]. Regularly, for a headlamp a thousand of lumen light output is required, which is converted from the electric energy of the battery charged by the automobile engine. Although the headlamp working time is only 25% of a day [3], the additional energy consumption or the operating cost of the headlamp cannot be omitted. For example, about 55 billion liters of gasoline and diesel or 66 billion USD costs are spent annually in operating the headlamp [4]. As reported by the U.S. Department of Energy [5], the electrical-to-optical power efficiency of LED luminaires is up to 30%, and it will surpass the 50%, meanwhile, the efficiency of the traditional ones is only 5% for halogen or 20% for xenon respectively. If the LED headlamps can replace all the traditional ones, the automobile will minimize the fuel consumption for the automotive lighting to 10%, and lead to a reduction of CO_2 emission by about 1–3 g/km [6].

Since the high power white GaN-based light-emitting diode (LED) has been invented in the 1990s [7], its application in the concept headlamp dates back to 2002 by Lighting Research center, USA [8]. There have been numerous attempts due to its longer lifetime, lower power demand, faster response time, more visual flexibility and closer to daylight color than the conventional light resources such as halogen and xenon lamps [9–13]. The first LED headlamp prototype is demonstrated by Hella cooperation, France in the 2005 [14], and recently, the commercial LED headlamp can be seen in such as LS600h [15]. Adaptive light beams can be realized by the simple electrical control in the LED headlamp rather than the mechanical control with motors in traditional headlamps. Besides, the LED headlamp also has a function of the visual light communication (VLC) [16], where the data can be transferred by modulating the LED output light. Therefore the LED headlamp is a hot topic in the current automotive industry.

However, the LED headlamp is still not in volume production. The reasons lie in the existing challenges in design and verification of the LED headlamp [17–19]. On one hand, the LED headlamp has a higher power density than signaling lamp [20], on the other hand, the operating environments and the regulated requirements of the LED headlamp are tougher than the general LED lighting such as street lighting [21]. Fortunately, the achievements of the general LED lighting [4,5] provide a clue to deal with these challenges.

In recent years, the electrical–optical–thermal physical issues of LED headlamps have been highlighted, and the unique features of the LED headlamp have been continuously addressed by many proposed design methods involving the thermal dissipation, the optical process, the electrical driver and the material structure, as well as the efficiency, cost, lifetime and reliability. Some of them, especially the thermal issue [22], investigated in certain literatures, reach a better design performance, but most of these attempts focus on a single physical field or unit of the LED headlamp. To the authors' knowledge, systematical and up-to-date review of the LED headlamp's progress is not found at present. To address the above point, this review tries to generalize the studies of the LED headlamp and summarize its technical achievements systematically; some important fundamentals of the LED headlamp are described firstly, then the status of the LED headlamp's design and verification are explored respectively, next, the development trends are illustrated, and a conclusion is drawn finally.

2. Fundamentals of the LED headlamp

Fig. 1 illustrates a boarding interface of the LED headlamp in a vehicle. The LED headlamp is fixed mechanically by screws into the vehicle's front body, powered from the electrical power distributor in junction box and controlled by light or body control module (BCM) through the CAN or LIN communication bus [15]. There are ambient factors (such as the temperature, humidity and dust) and usage conditions (e.g. frequency, maintenance and pollution) influencing the performance of the LED headlamp.

As a type of headlamp with functions of exterior decoration and lighting, the design of the LED headlamp still involves three topics including the geometrical structure design, the power control and management, the environment and usage durability. This review, however, mainly focuses on the last two topics because the geometrical structure design is a relatively dependent topic and out of our scopes.

The power control and management of the LED headlamp is realized by the four main components [15,23]: electrical drivers, LED array modules, thermal solutions, and lens or reflectors, as illustrated by the available products from Koito, Visteon, ZKW,

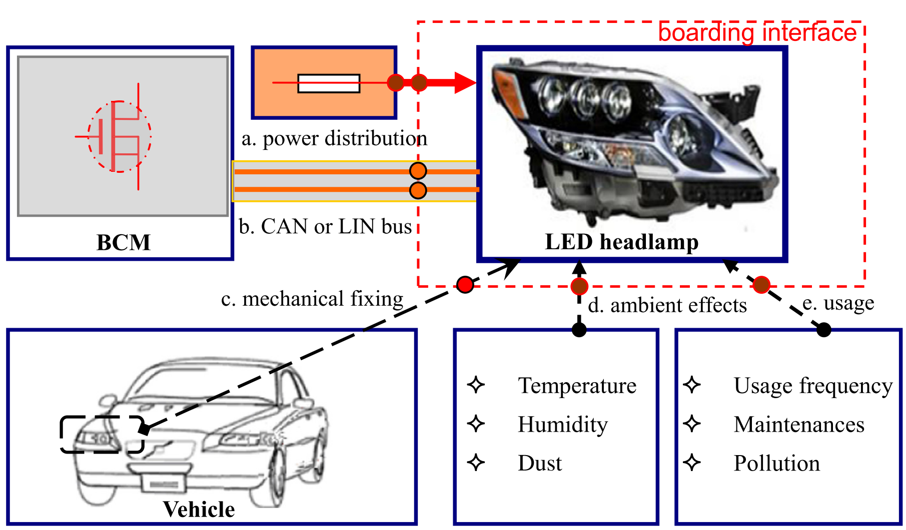


Fig. 1. Illustration of the boarding interface of the LED headlamp in a vehicle.

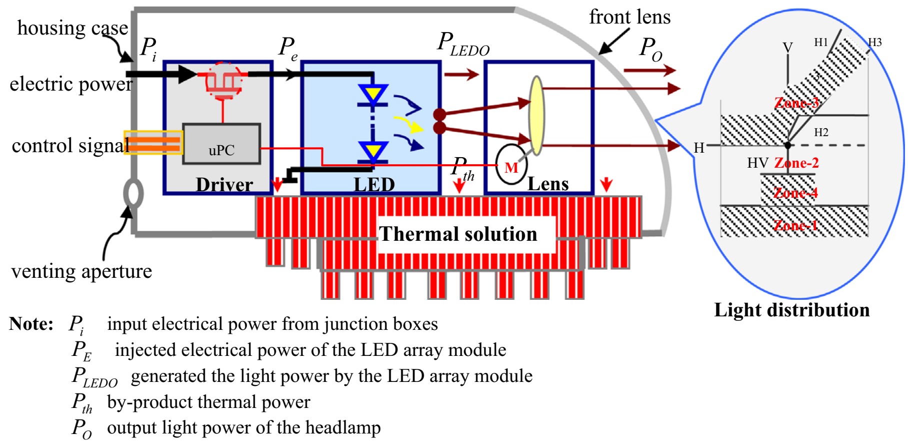


Fig. 2. Energy flow in the components of the LED headlamp. *Note*: P_i input electrical power from junction boxes P_E injected electrical power of the LED array module P_{LEDO} generated the light power by the LED array module P_{th} by-product thermal power P_O output light power of the headlamp.

Table 1
Main requirement and regulations of the LED headlamps.

Properties / Physical fields	Metrics	Key points	Regulations	Others
Optics	beam pattern	• low-beam	ECE R112	AFS:
	radiation distance	• 15°, 45° inclined cut-off line	SAE J1383-1996 GB 4599-2007	ECE R123
	color temperature		FMVSS 108	SAE J2591
Electrical	stationary	• negative polarity • wide range: e.g.6.5-90V for 12 V supply	ISO 16750-2 ISO 7637 SAE J1113-42	Semiconductor: AEC-123 AECQ100/101
	transient			
Thermal	temperature	• environmental temperature: -40°C -+80 °C		

Valeo, AL, Ichikoh, and ODELO [24]. Fig. 2 describes the energy flow in the components of the LED headlamp, from which we can see that the input electrical power from the junction box has a constant voltage (CV), and it is converted by the electrical drivers into the constant current (CC) waveform, which is required by the current–voltage (*I*–*V*) characteristics of the LED array module. The injected electrical power of the LED array module, controlled by microcomputer (uPC) unit, generates the light power as well as a by-product, thermal power. The output light power of the LED array module is processed by the lens or reflectors system with adjustment devices such as step-motor to obtain the regulated light distribution [18]. Energy losses or heats occur among these components, and then thermal solutions such as heat sinks are equipped to lower the too much high temperature. Therefore, the output light power of the headlamp is just a portion of the input electrical power, which is mainly determined by the efficiency of the components.

To address the environment and usage durability, there are numerous standards and requirements for the LED headlamp [25], out of them the optical regulations are of the most primary. The optical characteristics of the LED headlamp, including light distributions or beam patterns, optical power and color temperature (CT) [23], are closely related with the driving safety. Regulations, such as Economic Commission for Europe (ECE) R112, Commission of International Electric (CIE) 188, Society of Automotive Engineers (SAE) J1383-1996 and Chinese National Regulation GB 4599-2007 are typical standards for the beam patterns. And regulations for the low beam pattern [26] mostly focus on the maximum intensity, HV point, illumination in four zones, cut-off lines, as shown in Fig. 2. In addition, more beams patterns with adaptation to various conditions, called an adaptive front-lighting system (AFS) [27], are defined in Regulations ECE 123 and 48. Most of the optical regulations for the LED headlamp are derived from the traditional headlamps.

Apart from the optical regulation, the electrical, thermal–moisture, and mechanical standards are also important for the LED headlamp [25]. For instance, the 12 V supply used in automobile can have a wide range of terminal voltage, it can reach as low as 6.5 V during cold-crank and as high as 90 V during load-dump, and a wide temperature range from −40 °C to +80 °C, so the AEC regulations are required to qualify the semiconductors including LEDs [28]. Other regulations include AMEC FMVSS 108 for the humidity, Portland ASTM C150-77/ FMVSS 108 for the dust, FMVSS 108 for the anti-chemicals, and the EM compatibility in accordance with ECE R10. As a complex electrical–optical–thermal system, basic requirements and regulations for the LED headlamps are listed in Table 1.

3. Designs of the LED headlamp

The design of the LED headlamp is a complex project, and can hardly be stated clearly and completely. In this part, this project is reviewed in detail from the viewpoint of components [13,15]: the LED array module, the heat management, the optics control, and the driver electronics.

3.1. LED array module

The LED is a semiconductor diode, which converts the injected electrical charge into the photon with a specific peak wavelength or color. Contrasted to the traditional LED, such as the red LED fabricated from silicon material, the LED utilized in the headlamp is similar to that used for the general lighting, and that is, the LED for the headlamp is produced currently by combining the 560-nm YAG yellow phosphor with 460-nm blue LED die, which is a GaN-based multiple quantity wells (MQW) diode. The structure and material of the GaN-based LED die as well as its typical package methods [29], including the normal and the flip-down, are illustrated in Fig. 3. A detailed description on the structure, materials and carriers' transportation mechanism of the GaN-based LED is given by Schubert [7].

Although the performance of the LED reaches a state of the art, for example, the luminous efficacy is up to 100 lm/W [5], it is still challenged by the technique and non-technique issues, out of them the efficiency "droop" [30] and the temperature sensitivity

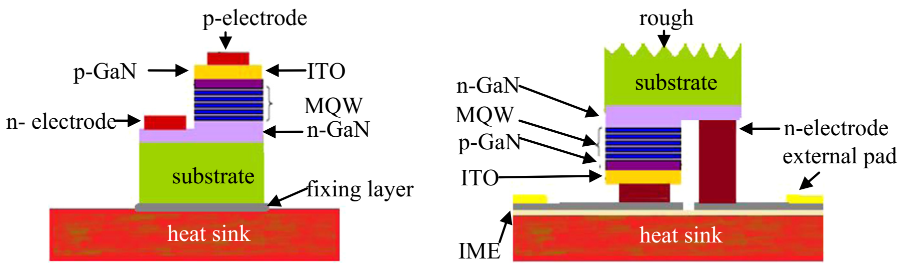


Fig. 3. illustrations of the package structures and materials of the GaN-based LED with a lateral die [29]. (left) normal method; (right) flip-down method.

Table 2
Challenges, mechanism and solutions of the two main issues of the LED.

Efficiency "droop":
The electric-optical efficiency is decreasing when the forward current density is large than a threshold.
challenges—much larger size of the LED to generate the higher power light output
mechanism—polar field, Auger combination or dislocation related carriers overflow under investigations
solutions—default control of GaN, integrate multiple LEDs
Temperature sensitivity:
The parameters, including the forward voltage, the luminous flux, the color temperature (TC) and the chromaticity coordinate are variable with the temperature.
challenges—decrease the junction temperature or enhance materials' temperature stability
mechanism—current crowd, energy gap modulation, degradations of the material
solutions—pads optimization, thermal management

[31] effect are the two of the most significance. And the challenges facing the LED, including the corresponding mechanism and solutions, are described in Table 2.

When the efficiency droop occurs, the current density of the currently available LED is very small, only 0.1–10 A/cm^2, comparing with the current density required by the LED headlamp such as 100–1000 A/cm^2. And this leads to a demand on LED array module which is a module integrating multiple LEDs as the light source to achieve hundreds of lumen output [32–35]. However, the design of the LED array module is a multiple physical field problem. And the design flexibility, the optical parameter uniform and the thermal resistance are necessary factors that must be considered to develop a favorable LED array module for the LED headlamp. But unfortunately, how to obtain the design optimization for the LED array module is a pending task at present.

Recently, many kinds of LED array modules have been proposed, which can be grouped into three types: multiple light points with multiple LEDs (MPML) [8], multiple light points with multiple chips (MPMC), and one light point with multiple chips (OPMC). For instance, [36] demonstrates a MPML, where a total of 48 pieces of 0.5 W and 0.25 W LEDs are used, and the LED array module has the length of 23 cm and width of 10 cm, respectively. However, the use of multiple LEDs in combination with optics is often constrained by the lamp size. Researches have shown that the MPMC and OPMC types of LED array modules are of a compact size, e.g. 17 mm in length and 15 mm in width [28]. More detailed comparisons among the three types are given in Table 3. Now the MPMC LED array seems to cast a light upon the automobile headlamp, especially the commercial available LED arrays such as the LUXEON Altilon LEDs from Philips Lumileds [37] and BXRA-W0401 from Bridgelux Co [38].

3.2. Heat management

The idea of thermal management for the LED headlamp was proposed 5 years ago, which involved thermal environment and design approaches and so on [22]. The main goal of the heat management for the LED headlamp is to maintain the temperature of the junction or active region MQW of the LED as low as possible while the design space and cost are allowable. Although the thermal power generated by the LED headlamp is much smaller than that of the traditional headlamps with the same input electrical power due to its higher electro-optical efficiency, and the heat of the LED headlamp is nearly dissipated by conduction, that is, from the junction to heat sink, and finally to air by convection; while only 10% of the heat generated by a traditional lamp is dissipated by conductive way [39]. Therefore, there are two basic ideas to manage the heat in the LED headlamp: one is how to shorten the length of the thermal conductive path from the LED's junction to the headlamp's ambient, and the other is how to choose materials with high thermal conductive coefficient as heat transfer medium.

In recent years, the thermal management in the LED headlamp has been widely studied from a viewpoint of multiple scales, including the chip-level, the package-level, the board-level and the system-level [40–43]. The chip-level solution is considered as one of the most essential methods, because the substrate of the LED die seems to be a heat bottle due to the widely adopted transparent sapphire substrate Al_2O_3, which has a low thermal conductive coefficient of only 25 $W/m\,K$ when the LED package is the normal type as illustrated in Fig. 3 (left). So a high thermal conductive coefficient substrate such as GaN or SiC was proposed. However the novel substrate-based LED still has a low efficiency. Then, the flip-down package, shown in Fig. 3 (right), another potential option was proposed, where the conductive path is through the p-GaN/pad and n-GaN/pad rather than the substrate. In addition, the chip-on-board (COB) technology [33,44], where the chip is bonded on the board (e.g. AlN) directly, become a mainstream to improve the heat management, and now the thermal resistance from the junction to board has been reduced to 1.3 °C/W [28]. More details about the solutions and their performances to the thermal management in LED headlamp are illustrated in Table 4.

All the great advances in the thermal performance for the LED headlamp are mainly attributed to the utilizations of the two modeling methods, that is, the equivalent thermal resistance and capacitor (RC) circuit model, the finite element (FE) simulation [45–48].

A typical thermal RC model of the LED headlamp is shown in Fig. 4(a), where T_a denotes the ambient temperature, and$R_{th,jb}$, $R_{th,ba}$ denote the thermal resistance from the junction to board and the board to the ambient respectively, and $C_{th,jb}$, $C_{th,ba}$ are the corresponding thermal capacitors. According to the RC model, the stationary junction temperature of the LED is [49],

$$T_{jn} = (R_{th,jb} + R_{th,ba}) \cdot P_{th} + T_a \tag{1}$$

The FE model of the LED headlamp, where the thermal solution is an active liquid cooling [40], is given in Fig. 4(b), the temperature distribution T at time t is followed the Fourier thermal

Table 3
Comparisons among the three types of the LED array module.

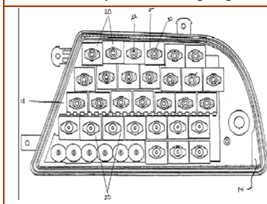
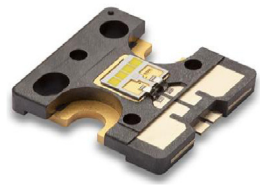
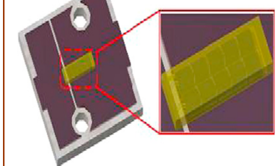
MPML: multiple light points with multiple LEDs [36]	**MPMC**: multiple light points with multiple chips [37]	**OPMC**: one light point with multiple chips [28]
		
Advantages: ⌖ flexible combination ⌖ uniform control easy ⌖ low thermal density	⌖ moderate size ⌖ moderate thermal density ⌖ good uniform control	⌖ one lens or reflector ⌖ compact size ⌖ compatible to traditional lamp
Disadvantages: ⌖ large space ⌖ complex beam control ⌖ compatible to traditional lamp	⌖ special lens or reflectors ⌖ compatible to traditional lamp	⌖ high thermal density ⌖ large deviation of the parameters, e.g. CT.

Table 4
The multiple-scale thermal solutions and their performances.

Chip level solutions:	
SiC or GaN substrate replacing sapphire	5 Times improvement in thermal conductive coefficients [5]
Substrate laser lift-off	
Package level solutions:	
Chip on board (COB)	$R_{th,jb}$ is 2 °C/W [40]
application specific LED packaging (ASLP)	$R_{th,jb}$ is 1.3 °C/W [28]
Board level solutions:	
Insulated metal substrate (IMS) with not filled thermal via	$R_{th,jb}$ is 7 K/W [37]
IMS with filled thermal via	$R_{th,jb}$ is 3 K/W [37]
System level solutions:	
Natural convection	Junction temperature of 200 °C [40]
Forced convection	The junction temperature can reach to 30.25 °C [42]
Liquid cooling	An improvement of 90 °C compared with that of the natural convection [40]

Note: $R_{th,jb}$ denotes the thermal resistance from the junction to board.

equation [50],

$$\rho c \frac{\partial T}{\partial t} = \nabla \times k_r \nabla(T) + P_{th} \tag{2}$$

here, ρ, c and k_r denote the mass density, thermal capacitor, and thermal conductive coefficient respectively.

Although the RC circuit model is simple and its parameters, including the thermal resistance and capacitor, can be measured experimentally by instruments [46] as illustrated in Table 4, there are some drawbacks including low space resolutions, non-constancy, and weak design ability. But these drawbacks are overcome by the FE model. Furthermore, the FE simulation provides the ability to optimize the parameters of the LED headlamp system

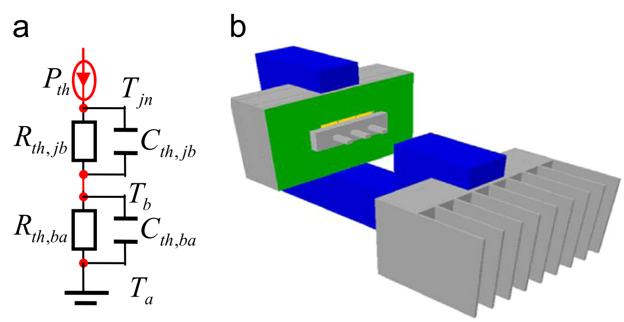


Fig. 4. Thermal modeling methods of the LED headlamp. (a) Thermal RC circuit; (b) FE simulation for LEDs with active liquid cooling [40].

[35,41]. For instance, Yan Lai et al. from Tyndall National Institute and Odelo Co [40] discuss an optimum thermal solution by optimizing the parameters of the heat sink including surface area, parameters of the fins (number, thickness and height), base thickness and material, which is constrained by the practical manufacturing and application conditions such as the weight restrictions and the space limitations. However, the computation cost of the FE method is so huge that it is impossible for the real-time application for thermal management of the LED headlamp.

Benefited from the results of the thermal solutions at different levels, their combination may lead to a better thermal management for the LED headlamp. Especially the new achievements such as the nano-engineering enhanced LED chips [5], COB with flip-down package and optimized insulated metal substrate (IMS) may play an important role in the progress. But how to optimize the combined multiple-scale solution is still an open topic, which is not a single physical task, but a complex problem involving multiple physical fields, where the optical, electrical and mechanic issues should be considered all together [36], and the constraints such as the cost, reliability and space should also be included.

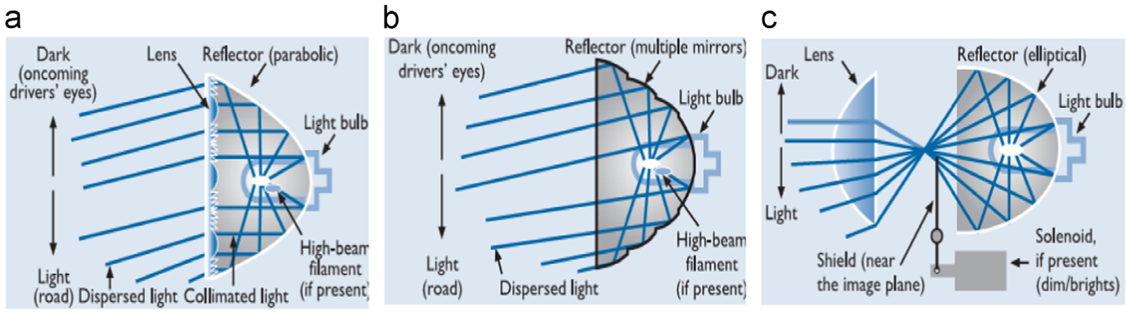


Fig. 5. The traditional configurations for headlamp optics [53]: (a) lens optics, (b) reflector optics and (c) projector optics.

3.3. Optics control

Contrasted to the conventional light sources, the spatial radiation pattern of the LED array module has a unique luminescence characteristic because of the Lambertian light intensity distribution of single LEDs and their space configurations [36]. In order to achieve a desired photometry performance including a specific light distribution (a beam pattern or comply with regulations [51]) and provide an innovative design, it is important to reutilize or redesign the traditional optical system, such as the refractor lens optics, reflector optics and combination projector optics, shown in Fig. 5. For instance, [52] propose a LED vehicle projector headlamp system containing four components: focused LEDs, asymmetric metal-based plates, freeform surfaces, and condenser lens. From the example we can see that the optical system for the LED headlamp implicitly consists of reflector optics, projector module, and lens optics [51].

In recent years, great efforts have been made to address the above mentioned issue [53], and the concepts [17], beam design methods and simulation technology [54,55] have been discussed. The suggested optical design methods mainly include the traditional optics [56], pixel lighting [57] where the target beam pattern is divided into multiple blocks and each LED illuminates one block, and non-imaging optics [28] including simultaneous multiple surface (SMS) method [58], 3D-tailoring, automatic optimization, and virtually reflecting/refracting surfaces (VRS). The properties of these methods are summarized in Table 5, and special attention should be paid to the types of light sources: point-, line- and matrix-type, because the available LED array module, OPMC, MPMC, or MPML as stated in Section 3.1, usually can be considered as one of the important factors contributing to a good design.

In traditional optics design, there are two distinct advantages, one is low optical variation and the other is simple creation of the cut-off line. It is because of these two advantages that the traditional optics design method is more popular than the recently developed methods. However, when the traditional optic methods are adopted, the light source of the LED headlamp must be point-like such as focused five pieces of 3-Watt LED [56], and the optical efficiency is lower down due to additional stops such as asymmetric metal-based plate.

The pixel lighting and non-imaging optics methods show abilities of high optical efficiency and optical design for other light sources. For instance, [36] illustrates a pixel lighting based low-beam headlamp with a high optical efficiency up to 85%, where 14 pieces of 0.5 W LED were used to illuminate the road ahead, and 29 pieces of 0.25 W LED were used to illuminate the closer road and both sides of the road, and the 45 degree inclined cut-off line in the regulation is realized by lighting up the 0.5 W LED which locates at the top left corner. Moreover, the drawbacks of the pixel lighting and non-imaging optics methods facing for years will be avoided, when the color consistency is improved from 7-step, 5-step towards to 2-step MacAdam Ellipses [5] and the manufacturing process of special optical devices such as rectangular beam lens [36] and freeform multi-reflector [28] will be better soon.

A more flexible light distribution and multiple exquisite designs such as AFS system can be achieved by matrix-like light source such as MPML and MPMC, and its optical control can be designed by the pixel lighting method. Therefore, the pixel lighting method provides a better future for the LED headlamp industry when the critical issues, such as the electrical driver and controls, are solved in the near future.

Table 5
Optical design methods of the LED headlamp.

1) Traditional optics	
Application type of LED sources:	Point-like
Features:	traditional lens, reflector, and projector optics [53] using additional stops to create the cut-off line[56] forms a virtual point source with several LEDs
Advantages and disadvantages:	**less** illuminance and color variation **simple** manufacturing process **low** optical efficiency
2) Pixel lighting	
Application type of LED sources:	Matrix
Features: independent beam	additional secondary lens e.g. rectangular lens[36] LED's on/off control to generate the beam pattern
Advantages and disadvantages:	**large** illuminance and color variation **difficult** manufacturing process **high** optical efficiency e.g. up to above 85% [36]
3) Non-imaging optics	
Application type of LED sources:	line-like and matrix
Features: overlapping light	non-conventional reflection/refraction optics e.g. freeform multi-reflector [28] create cut-off lines without additional stops [25] combine LED's own spectral distribution to achieve the beam pattern consistent with the regulation.
Advantages and disadvantages:	**large** illuminance and color variations **complex** manufacturing process **moderate** optical efficiency e.g. up to 75% [58]

3.4. Driver electronics

In vehicles, the constant current (CC) is the best operating current for the LED array module [59] to produce consistent lighting when the voltage fluctuation occurs. There are two types of power source to realize the CC output at given input voltages and deliver an output voltage equal to the sum of the maximum

forward voltage of the LED array module at the same time, that is the linear regulators and switch converters [60,61]. The linear CC regulator is an adjustable linear voltage regulator whose feedback voltage is from a current-sensing resistor, and thus leads to low convert efficiency and an additional thermal issue. So the switch type CC converters are usually adopted to replace the linear CC regulator in the LED headlamp even though the linear regulator with no electromagnetic interferences (EMI) can be designed and realized simply [62].

There are three topologies of switch type CC converters: Buck or step-down, Boost or step-up, and buck–boost or Cuk. The principles of these converters are fully discussed in [63]. The application considerations including the relationship between the input and output voltage and the fundamental characteristics sucn as the efficiency are discussed in details. For instance, the Buck (or Boost) CC converter has higher efficiency e.g. 98.04% of LM3402HV than that of the buck–boost CC converter e.g. 88.98% of LM3423 [64]. But the buck–boost CC converter can meet the electrical characteristics in the automobile where the input voltage overlaps the forward voltage of LED array module. For example, a nominal forward voltage of about 12 V for 1 × 4 array Altilon LEDs [37] is the output of the buck–boost CC converter, whose input voltage might be above or below the output due to a wide supply voltage ranging from 6.5 to 90 V, seen in Table 1. With the increasing convert efficiency, the buck–boost CC converters are more and more widely applied in the LED headlamp.

The constant current is usually modulated with a typical pulse-width waveform (PWM) in order to dim the light level of the LED array module [34]. For a given peak current and frequency of the PWM, the LED luminous output without visual flicker or discomforts is closely linear to the PWM duty. Serial and parallel MOSFET switch methods are proposed to realize the PWM seeing Fig. 6, and their advantages and disadvantages are surveyed in [65].

To map the sensor signals from Bus into the PWM duties, the driver consists of the CC power supply with serial or parallel MOSFET and the microprocessor (uPC) controller unit. For example, [38] presents a 40 W/l.4 A/28.5 V digital single-ended primary inductance converter (SEPIC) to drive the LED arrays of an automobile LED headlight system, which consists of 2 parallel strings with 3 arrays connected in series. The adaptive feature of LED headlights is demonstrated in the LED driver by dimming the LED output to half when the automobile is running at zero speed. The uPC is considered as the potential driver topology to address ease of controlling, which forms the natural of intelligent lighting system based on vehicle sensor inputs [66].

Benefited from the digital driver topology, different LEDs can be lighted up to obtain the right beam pattern automatically as the traditional advanced AFS [10]. A simplest example is the realization of high beam and low beam patterns by turning on and off, or bi-level lighting for a special LED configure [54], where five modules of lens are arranged adjacent to each other in the upper part of the headlamp to produce low beam and two vertically mounted side-positioned modules to produce high beam. Although the adjustment unit is still one of the necessary functional structures to adjust the lens up and down or sideways in the factory commissioning process and driver user, for example, Yanqing et al. [53] gives the designs of the modified traditional

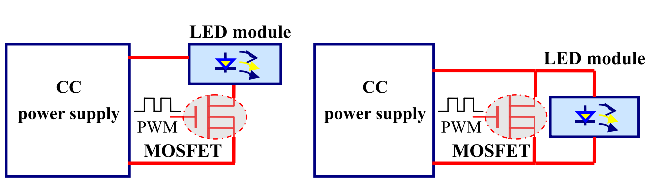


Fig. 6. The methods of realizing CC PMW for LED array module.(left) serial MOSFET [21], and (right) parallel MOSFET.

adjustment mechanism based motors aiming at the 7 LED lights source system of Besturn B70 LED high beam, variable light controls of the LED headlamp have been realized by the electronic means rather than the traditional mechanical parts, e.g. a digital micro mirror device (DMD) [67–68].

Recently, more and more beam modes, such as beam patterns related with highway speeds, weather conditions and for cornering [36], can be activated purely by the electronic means [3,54] with the development in multiple-channels digital PWM driver and freely-addressable LED-arrays [18]. However, the current balance among different channels [61] and the compact package of multiple chips with multiple terminals are still the two big challenges. Moreover, the precise and accurate of the processing algorithm in digital driver hinder the development of the beam pattern control. To address this issue, a camera is additionally used, and traffic information is detected based on images [38,69]. For instance, [70] reports an enhanced AFS with a vehicle Kanade–Lucas–Tomasi tracker based on the ULO camera from ODELO.

In summery, the driver electronics in the LED headlamp fulfill the functions of: (1) providing the LED array modules with a constant forward current to produce consistent lighting when the supplied voltage fluctuation occurs in a vehicle; and (2) dimming the lights or controlling the adjustment unit to fulfill the regulated beam pattern according to the control signals.

4. Verifications of the LED headlamp

The LED headlamps have been so far prevented from widely entering the market by the operational concerns, such as low plug-in efficiency, high production costs, low reliability related with temperature and moisture and so on [18], which leads to verifications of the LED headlamp.

4.1. Plug-in efficiency

Due to the energy crisis, one of the goals of the LED headlamp is to achieve a higher efficiency by virtue of the high efficiency of LED to reduce energy consumption. Currently, some reports show the efficiency of LED headlamp surpasses that of traditional halogen light. For example, 12 W 2-LED-devices based headlamp, with an ECE regulation required low-beam pattern, reach a 78.18% energy saving compared to a low beam 55w halogen light [71].

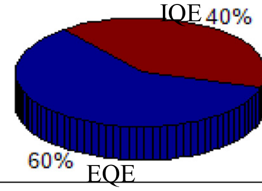
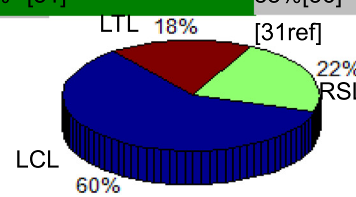
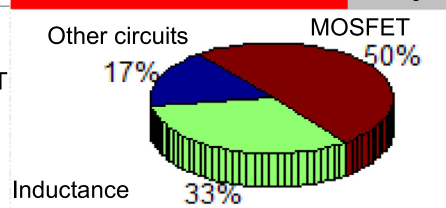
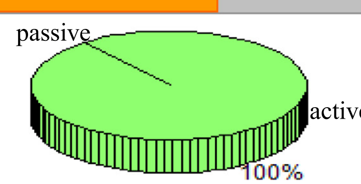
With the advent of design methods as given in Section 3, the efficiency of the components in LED headlamp has been increasing in the past years. Table 6 gives the reported efficiency and the loss contributions of the major components in LED headlamp. The plug-in efficiency is determined by the efficiency of all components,

$$\eta_{plug-in} = \eta_{LED} \times \eta_{optic} \times \eta_{driver} \times k_{th} \quad (3)$$

where η_{LED}, η_{optic}, η_{driver} indicate the efficiency of LED array module, optics system, and driver, respectively. And $k_{th} \in (0, 1]$ is the thermal solution loss factor, specifically k_{th} is 1 if the passive thermal solution is adopted.

Although the efficiency of each single component reaches an art-of-state, especially the driver electronics up to 94.9% [38] and the lenses of more than 88% [36,72], the plug-in efficiency is still low because of the 60% optical efficiency [54,73] and 20% LED efficiency, and even an additional electric power loss from the optional thermal management. In 2013, for instance, [73] reports total optical efficiency is only 40.2% by using the total internal reflection (TIR) lens, prism splitter and light pipe in LED headlamp. Practically, modern optics such as the TIR with reduced length of LED headlamp from 90 mm to 53 mm [74] is challenged by the tradeoff between the efficiency and cost, and the traditional optics

Table 6
The efficiency and the losses of the components in LED headlamp.

LED array module	
Efficiency:	20%*[28] 52%**[75]
loss factors' portions [75]: ✧ internal quantum efficiency (IQE) ✧ external quantum efficiency (EQE)	
Headlight optics:	
Efficiency:	60%* [51] 88%[36]** [31ref]
loss components' portions[51]: ✧ light collection loss (LCL) ✧ reflecting surface loss (RSL) ✧ lens transmission loss (LTL)	
Driver electronics:	
Efficiency:	90%*[28] 95%**[28]
loss components' portions: ✧ semiconductor switches e.g MOSFET ✧ Inductance elemen ✧ Other circuits including passive capacitors, resistors	
Heat management:	
electric power loss factor:	0-1* 1**
components loss portions: ✧ active element ✧ passive element	

Note: * denotes the mainstream value, and ** denotes the maximum value.

based LED headlamp is the more cost-effective system. However, the maximum optic efficiency of traditional optics is only 45% in a parabolic based reflector optic system [51]. Therefore, the electric-optical efficiency of the LED module is significant to improve the plug-in efficiency of LED headlamp.

Contrasted with the traditional headlamp's light efficiency such as Halogen bulb H7 of 25 lm/W and Xenon lamp D2S of 91 lm/W [23], the efficiency of the available automobile LED is around 80 lm/W currently [37]. Although the efficiency of the automobile LED reaches the range of the Xenon lamp, it is still lower than that of the general lighting LED. For instance, 150 lm/W of the general LED at 700 mA is announced by Cree Inc in 2011, and 251 lm/W is the theoretical maximum value. The efficiency of the automobile LED shows a great potential to improve the plug-in efficiency if it can benefit from the general LED lighting, seeing Fig. 7.

The progressive development of LED manufacturing techniques [75], such as surface rough, conformal phosphor coating method, and UX:3 chip technology from Oslon Black Flat, Osram [76], has maximized the IQE and EQE of the LED module, which leads to a great increase of the LED efficiency from around 50% to over 90%

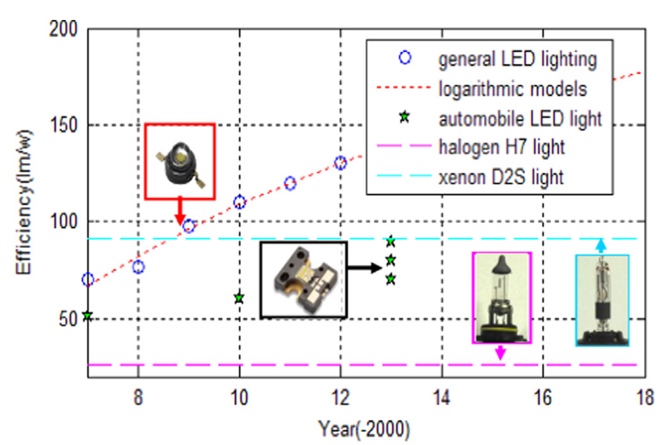


Fig. 7. Efficiency comparisons among the automobile LED, the traditional light sources and the general lighting LEDs. *Note***:** (1) general LED lighting data from Strategies Unlimited for average lm/1w package [76]; (2) using logarithmic model [5] fits the general LED lighting data with R-square: 0.98; (3) automobile LED from Osram, Lumileds, Nichia, Toyoda Gosei and Stanley Co.

during the last ten years. There is a promise of even higher efficiency in the near future, which will promote the designing of high efficient LED headlamp greatly.

4.2. Cost

Currently, the cost of comparable LED headlamps is about 350% higher than halogen headlamps and 100% higher than HID xenon headlamps. The cost structures of LED headlamps is revealed in [77] and its detailed comparisons with traditional halogen and HID headlamps is shown in Fig. 8.

Reduction in the price of LED headlamps has accelerated over the past year [19], which was caused by their cost-down productions and cost-effective designs of the main components as illustrated in part 3. At present, the low-power LED of 0.5 W rather than the high-power LED of 3 W is considered to not only promote the system efficiency but also reduce the cost [36], because low-power LEDs need no additional reflectors, which leads to high reliability in installation and partial realization of the functions of AFS. Even thought the available LED headlamps have already reached the light levels of traditional halogen headlamps, they are less likely to compete with these traditional headlamps because of their higher price, and this is what puts them currently into competition with other high-end sources. The cost of the LED headlamp is expected to be comparable to the traditional lamps in the near future. Mckinsey and Company, Inc. suggests that [77] the average annual cost reduction from 2009 to 2015 is about 13%, and the average selling price of LED headlamp might reach to 127 USD in 2015, parity with Xenon-based headlamps.

As the Haitz's law states, on the price trend of LED [5], the cost per lumen falls by a factor of 10 every decades. In 2012, the USD/kilo-lumen (KLm) of LED in general lighting applications is 3.45, and while 32 USD/ KLm in 2007 [76]. Considering the safety-related and recall-prone issues in vehicles, however, the LED in headlamp applications is more expensive due to extra process steps, more inspections and additional equipment maintenance compared to that of general lighting LED. For example, the expensive binning step for color characteristics, which refers to the classification of production yields, is usually adopted to achieve a high color consistency such as 2-step MacAdam ellipses [8]. Moreover, the back-end production cost of the LED is the largest cost components up to 54.9% [75] including the huge investments in LED chip/package production lines, and its scale effects will decrease the LED price. For example, LED package price reduction from 2010 to 2015 is 13%, where price is 1.00 to 0.58 USD for a high power LED [78]. In addition, larger wafers in before-end process, vertical integration of the LED chain after market [77] and efforts of tier-one supplier branding have a great impact on LED cost savings. The inflection point for the LED could be around 2015 according to the McKinsey's 2012 analysis [78].

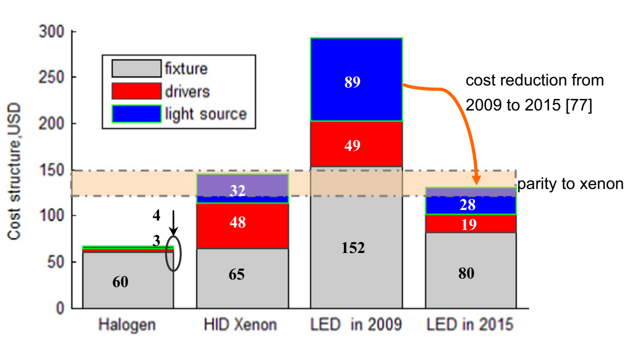


Fig. 8. Cost structures of the headlamps with LED, halogen and HID.

Although LED headlamps are the most desired technology for new car buyers according to the J.D. Power report, the cost of the LED headlamp remains a hurdle to its market penetration in mainstream [77], rather than just high-end automotives.

4.3. Reliability and lifetime

The LED headlamp often operates under high-stress conditions [18], for example, moving at 100 km per hour in a −10 °C evening, quickly self-heating to 70 °C, while enduring road shocks and engine vibrations. Thus as the time goes by, its performances potentially occur degradations and even catastrophic failures, so-called the reliability issue and lifetime, of which the oxidizing of electrical connections [79], freezing on front lens, color shift [80,81], lumen depreciation [82], unstable output or no light output are typical phenomena. The reliability means the probability to repair or replacement, while lifetime is the time length of service. Similar to the traditional headlamps, there are many causes for the reliability and lifetime of the LED headlamp including noise, control factors and input signals, seeing Fig. 9. The reliability and lifetime are closely related with not only the plug-in efficiency and maintenance cost, but also the safety of the electronic driver. Therefore, studies on the reliability and lifetime of the LED headlamp are always considered as critical topics beyond performances.

Due to the above factors, various kinds of tests on accelerated degradation (ADT) (temperature, humidity, dust and vibration), anti-radiation (ultra-violet, chemicals) and electro-magnetic (EM) compatibility have been carried out to study the reliability and lifetime of LED headlamp. Besides the shock, vibration and scratch, the adverse weather conditions, especially the high moisture and temperature, are considered as the principle factors to the reliability and lifetime of LED headlamp [22,46]. This point of view is highlighted in the development of the LED headlamp of Varroc lighting systems, Czech Republic [10]. Moreover, the corresponding industry standards have been proposed as illustrated in Part 2.

It was also revealed that the premature or catastrophic failures in driver electronics [38], housing component and LED package [37,40] are the principal failures of the LED headlamp. Each failure has a different portion in total failure issues. For instance, if the thermal management of the LEDs is well addressed, the driver electronics, especially the power supply due to the age of the fluid-filled aluminum electrolytic capacitors (e-cap), is the largest contributor up to 59%; the housing component is the second accounting for 31%, and the LED package is the third only accounting for 10% [83]. Furthermore, the LED, e-cap, solder joints (s-joint) and lens are revealed to be most sensitive to these factors [84]. In order to understand the physical mechanism of the failures, the thermo-mechanical fatigue, electro-migration, moisture diffusion and material degradation micro process are usually analyzed [85,86]. Fig. 10 illustrates the mechanism structure between the failures and the responding factors.

Recently, to qualify the LED headlamp's reliability and lifetime, mathematical and physical methods are utilized to model the service time and the failure probability of components. Arrhenius based LED lumen maintenance model [31] and bathtub curve probability distribution [87] based catastrophic failure model are the most popular mathematical models for projecting the LED lifetime and catastrophic failure rate under different factors. For instance, the probability of a catastrophic Luxeonrebel LED failure, impacted by the junction temperature of 100 ppm (or reducing 0.001%), is estimated to 4000 h [43]. Another example is that every 10 degree drop in operating temperature of e-cap would double its lifetime [88]. A main reason for this phenomenon is vaporization of electrolyte, which in turn leads to a reduction in lifetime indexes of the

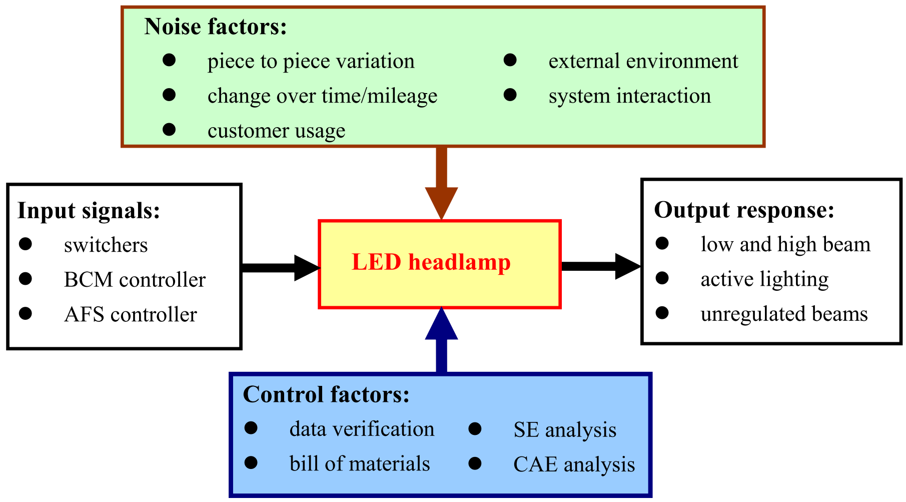


Fig. 9. Block schedule of influencing factors on the LED headlamp's lifetime and reliability.

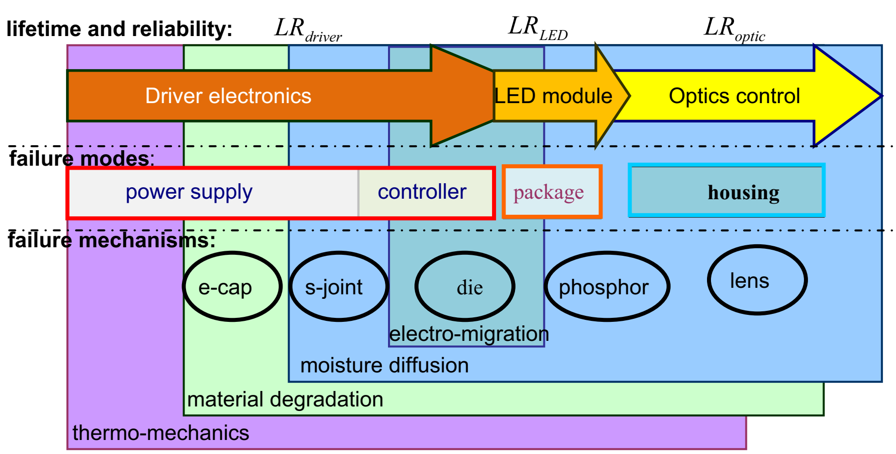


Fig. 10. Mechanism structure between the failures and the influencing factors.

equivalent series resistance and the capacitance. The root causes for the observed rule in e-cap are summarized in [88].

The Fourier thermal conduction equations, fluid dynamics equation, humidity diffusion model as well as thermo mechanical model [22,48,89], derived from the physical mechanism of failures, are the typical physical models to qualify the essential parameters such as junction temperature, Rayleigh number, expansion ratio. [42] reports that the reliability of the LED headlamp is estimated by the Fourier thermal equation based finite element simulation, where the junction temperature of LED arrays is investigated at different parameters of the cooling system. Currently, the mathematical and physical models are simultaneously focused on the components of the LED headlamp [39], especially on the risk estimation of the LED module [10] and the optical device. For example, with the Monte Carlo simulation method, the combination of the lumen maintenance model and catastrophic failure rates model is used to predicate the failure probability of a LED array accurately, and the test on a 32-LED array suggests a failure probability of 20% at 230k h [43]. However, there is little reported about the reliability and lifetime models of the whole LED headlamp system.

The optimization simulations based on the above mentioned models now have a trend towards maximize the LED headlamp's reliability, cost-effectively and lifetime, e.g. a statistics-based uniform parameter design from Hella, Germany [10]. Many experiments, such as the thermal measurement of a plastic-made housing case or lens using thermocouples, IR-thermograph or laser-Doppler velocimetry [79,89], the junction temperature measurements with the forward voltage based direct method or thermal resistance based indirect method [36,90] and so on, have been done to reach a more accurate assessment of them.

However, the testing, assessment and optimization of the LED headlamp's reliability and lifetime is a difficult life-cycle task, involving knowledge of design, production and usage. The optimal deign solution dealing with the noise factors is obtained from not only an isolated aspect, such as aggressively junction temperature management [40,43], but a multi-physics and multi-scale aspects, such as general photo-electro-thermal theory [91], where the cost, efficiency and ambient boundary conditions should be balanced. Therefore, some pending failure such as lens freezing [22] can be successfully solved. And more factors are taken into consideration to model the reliability and lifetime of the LED headlamp as a whole system. In addition, new materials and techniques, such as less moisture absorbed ABS, non-yellowing polycarbonate lens and a scratch-resistant hard coating, are potential ways to obtain a maintenance-free LED headlamp in the future.

5. Trends of the LED headlamp

Due to the digital and all-color available characteristics of the LEDs, the LED headlamp might have the ability of communication as well as integration of human factors in the future.

The development trend of the LED headlamp with the visual light communication (VLC) function has been increasingly speed up by researchers. The VLC function means that the LED headlamp can perform the function of car-to-anything technology [92] while maintaining the original forward lighting function by modulating the LED output light with a kHz or higher switch frequency to transfer data without sacrificing the quality of beam patterns. For example, LED-IT fusion technology research center from the Yeungnam university, republic of Korea [93], demonstrated a vehicular car-to-car VLC system based on prototype LED headlamp, where the inverse 4-PPM scheme with 75% dimming is used, and it has 10k bps data rate in about 20 m distance at day time [16].

With the wide implement of the intelligent transportation system (ITS) in road safety applications [94,95], the LED headlamp with the VLC function will open up new ways to improve the active safety. However, the VLC of LED headlamp just stay at a start-stage, and currently, the communication performance is difficult to be reliably used in practical environments [94]. There are still many technique and non-technique challenges including: how to improve the signal-to-noise ratio, transmission distance, as well as the data rate. It is also an issue worthy of study whether the fast-pulse-out light can improve the potential safety, which is similar to the low frequency considered in IEEE 1789.

The other development trend of the LED headlamp is that the output light beam, including patterns and spectrum distributions, is integrated with the human factors such as ages [2,96]. AFS system [27,69], where the headlight intensity is controlled based on the speed, distance between the vehicle and other vehicles, weather condition and type of the road, is a typical application using the human factors. Another example is that the LED headlamp with correlated color temperature (CCT) of 5000 K is suggested to be more comfortable for the driver because the CCT is near to that of the daylight [84]. Researches show that human factors engineering based headlamp design improves driving safety by reducing the frequency of crashes at night through enhancing driver's visibility [1,97].

More human factors, especially the eye's photopic, scotopic and mesopic vision [8], might be addressed by fully using the LED's unique characteristics of configurable spectral distributions. [32] shows a design of combination headlamp based on a special COB packaged module with all color ultra bright LED (ACULED). As illustrated at the eye, the brain and the auto conference, hosted by the Detroit institute of ophthalmology in Dearborn, Michigan, during Sept. 16–18th, 2013, the adaptive high beam headlight system can have more safety benefits than low beam headlights.

However, the spectral distribution of the LED headlamp, for example the peak wavelength, the percentage of red light and the scotopic and photopic (S/P) ratio, is different from that of the traditional lamps [17], and thus leads to some negative effects [84] such as the color difference of the road signs [98]. Moreover, assessment on safety effects of vehicle lighting is very difficult, even when the devices considered are "classical" lamps. And this evidences that the same kind of research on LED headlamp will be a more complex task [99]. More researches on the visibility analyses such as relative visual performance (RVP) model [2], developed by lighting research center (LRC) at Rensselaer Polytechnic Institute Mark Rea. Bullough and Rea, are expected to increase peripheral visual performance, reduce glare [96,99], and improve customer preference.

Although the above mentioned trends show a good promise for the LED headlamps, these novel designs might bring new challenges to electronic driver, experimental verification and evolved standards [10,26]. Moreover, it seems that there is a conflict between the innovation and the regulations. Ref. [17] shows that LED headlamps have been approved in North America according to the SAE standards, while the regulatory environment in other regions is still a barrier. An outlook of the dates for legalization is expected. Therefore, both the technical considerations and the safety regulations should become the start point for developing the LED headlamps to reach the final objective: to see and to be seen.

6. Conclusions

Over the past decade, several reasons aroused the interests of automobile engineers and designers into the LED headlamp: it occupies less space, consume lower energy, and longer lifetime. However, until now the market suggests that the LED headlamp is still standing at the start line other than the end. This paper brings a knowledgeable insight into the LED headlamps, and some important clues to its future development have been concluded as the following:

(1) The four main components of the LED headlamp are reviewed to address the status of the advancing technique, the multi-scale and multi-physical field optimization design for the LED array module and head optics are illustrated as the main approach to improve the efficiency and reliability;
(2) Several regulations about reducing glare for oncoming traffic while giving adequate illumination within safe braking distance have to be met and even be enhanced, because of the unique spectrum characteristics of the LED;
(3) The developments of energy-efficient thermal management, adaptive driving beams and functional controller ensure the markets and consumers really benefit from the LED headlamp;
(4) The visual light communication (VLC) function of the LED headlamp might be one of promising technologies in road safety applications, however, there is still a long way to go to fully realize the features;

In a word, LED headlamps should experience a long period of sustained growth, and be gaining popularity.

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References

[1] Dewar Robert E, Olson Paul. Human factors in traffic safety. 2nd ed.. . Tucson: Lawyers & Judges Publishing Company; 2007.
[2] Bullough John D, Donnell Eric T, Rea Mark S. To illuminate or not to illuminate: roadway lighting as it affects traffic safety at intersections. Accid Anal Prev 2013;53:65–77.
[3] Götz M, Kleinkes M. Headlamps for light based driver assistance. SPIE Int Soc Opt Eng 2008;7003:1–10.

[4] International Energy Agency. Light's labour's lost: policies for energy-efficient lighting; 2006. Available online ⟨http://www.iea.org/publications/freepublica tions /publication/light2006.pdf⟩.
[5] U.S. Department of Energy. SSL pricing and efficacy trend analysis for utility program planning; 2013. Available online ⟨http://www1.eere.energy.gov/build ings/ssl/tech_reports.html⟩.
[6] Leo Lorenz. Power semiconductor–state of the art and development trends; 2010. Available online ⟨http://www.drive-e.org/wp-content/uploads/vortraege_2010/16_Fr_Lorenz_PowerSemiconductiors.pdf⟩.
[7] Schubert EF. Light-emitting diodes. 2nd ed.. Cambridge: Cambridge University Press; 2006.
[8] John F V Derlofske, Michele W McColgan. White LED sources for vehicle forward lighting. In: SPIE second conference on solid state lighting, 4776. 2002. 1-12.
[9] Bolander A, Brooks T, Thompson P. LED headlamp for DOE super truck. SAE Tech 2013. http://dx.doi.org/10.4271/2013-01-0753 (paper 2013-01-0753).
[10] T Q Khanh. In: Tenth international symposium on automotive lighting. Herbert Utz Verlag; 2013.
[11] Asmarashid P, Azila N A M, Sor, Ariffuddin J, Handy A Munir. Development of vehicle lighting system using LED application. Int J Integr Eng 2011;3:11–5.
[12] Kajiyama Shigetoshi, Machida Tsutomu. Automotive LED headlamps. IEEJ Trans Electr Electron Eng 2009;4:12–3.
[13] Neumann R. LED Headlamps in automotive lighting-opportunities for all vehicle segments. CIE 27th session of the international-commission-on-illumination 2011:10–5.
[14] LEDs Magazine. LED headlamps from Hella to appear on Cadillac; 2005. Available online ⟨http://ledsmagazine.com/news/2/9/8⟩.
[15] Jih-Tao Hsu, Tse-Hsiu Yen, Hsuch-Lung Liao. Analysis result and study of LED head light sets-take LS600h head lights for example. 2009, p. 1–6. Available online ⟨http://www.artc.org.tw/chinese/03service/03_02detail.aspx?pid=1491⟩.
[16] Jong-Ho Yoo, Rimhwan Lee, Jun-Kyu Oh, Hyun-Wook Seo, Ju-Young Kim, Hyeon-Cheol Kim, et al. Demonstration of vehicular visible light communication based on LED headlamp.In: KICS fifth international conference on ubiquitous and future networks; 2013, 465-467.
[17] Thomas Luce. LED headlamps-the spiny path to a legal headlamp. In: Proc. SPIE photonics in the automobile, 5663. 2005. 112-121.
[18] Wolfgang Pohlmann, Thomas Vieregge, Martin Rode. High performance LED lamps for the automobile: needs and opportunities. In: Proc. SPIE 6797, manufacturing LEDs for lighting and displays; 2007. 1-15.
[19] Mak Kevin. LED headlights: styling drives growth, control and cost challenges remain. Strategy Anal 2013:1–83 (Available online).
[20] Landau Steve, Erion Jeff. Automotive: car makers embrace LED signals. Nat Photonics 2007;1:31–2.
[21] Long X, Liao R, Zhou J. Development of street lighting system-based novel high-brightness LED modules. IET Optoelectron 2009;3:40–6.
[22] Daniel N. Donahoe. Thermal aspects of LED automotive headlights. In: IEEE vehicle power and propulsion conference; 2009. 1193-1199.
[23] Eichhorn Karsten. LEDs in Automotive lighting. SPIE light-emitting diodes: research, manufacturing, and applications X 2006;613405:1–6.
[24] Electronics Weekly. Car makers focus on LED headlights; 2013. Available online ⟨http://www.electronicsweekly.com/news/components/led-lighting/car-makers-focus-on-led-headlights-2013-03⟩.
[25] André D, Udo R, Simon W, Karsten K, Dieter K, et al. New design tools for LED headlamps. SPIE Opt Sens 2008;7003:1–10.
[26] International Standard. Automotive headlamps with LED light sources and/or LED module [Standard Draft for Approval]; 2012. ICS43.040.20.T38.
[27] Peña-García A, Peña P, Espín A, Aznar F. Impact of adaptive front-lighting systems (AFS) on road safety: evidences and open points. Saf Sci 2012;50: 945–949.
[28] Fei Chen, Kai Wang, Zhangming Mao, et al. Application specific LED packaging for automotive forward-lighting application and design of whole lamp module. In: Electronic components and technology conf., 2012 IEEE, 2012, 182-186.
[29] Xingming Long. Research on electronic–optical–thermal characteristics of InGaN/GaN lighting emitting diode based electronic-thermal aging test and its optimum forward current. [Doctor thesis]. Chongqing University, China; 2012.
[30] Piprek Joachim. Efficiency droop in nitride-based light-emitting diodes. Phys Status Solidi A 2010;207:2217–25.
[31] Ȑurmen M, Pernuš F, Likar B. LED light sources: a survey of quality-affecting factors and methods for their assessment. Meas Sci Technol 2008;19:1–15.
[32] Technology: Optoelectronics. Concept car exploits multi-chip LEDs for headlamps. III-Vs Review 2006;19:19.
[33] Long X M, Liao R J, Zhou J, Zeng Z. Multiple-chip package embedded on compound board for light emitting diode. Electron Lett 2011;47:1142–4.
[34] Peter Brick, Tobias Schmid. Automotive headlamp concepts with low-beam and high-beam out of a single LED. SPIE conference on illumination optics II 2011;817008:1–11.
[35] Lin Qi, Chunqing Wang, Yahong Tian. Thermal design of a LED mulit-chip module for automotive headlights. In: IEEE 13th international conference on electronic packaging technology and high density packaging 2012:1435–8.
[36] Zhu Xiangbing, Zhu Qian, Wu Han, Chen Chun. Optical design of LED-based automotive headlamps. Opt Laser Technol 2013;45:262–6.
[37] Elger Gordon, Lauterbach Reinhard, Dankwart Kurt, Zilkens Christopher. Inline thermal transient testing of high power LED modules for solder joint quality control. In: IEEE 61st electronic components and technology conference 2011:1649–56.
[38] Wu Li-ming, Huang Tai-xiang, Kuan Kan-sheng. Analysis and design of digital SEPIC converter with programmed dimming and current sharing for automobile LED headlights application. In: IEEE seventh international power electronics and motion control conference 2012:215–21.
[39] Langebach J, Senin S, Karcher Ch. Experimental study of convection and radiation interaction in a headlight model using pressure variation. Exp Therm Fluid Sci 2007;32:521–8.
[40] Lai Yan, Cordero Nicolás, Barthel Frank, Tebbe Frank, Kuhn Jörg, Apfelbeck Robert, et al. Liquid cooling of bright LEDs for automotive applications. Appl Therm Eng 2009;29:1239–44.
[41] Hu Shuhong, Yu Guiying, Cen Yichao. Optimized thermal design of new reflex LED headlamp. Appl Opt 2012;51:5563–6.
[42] Sunho Jang Moo Whan Shin. Thermal analysis of LED arrays for automotive headlamp with a novel cooling system. IEEE Trans Device Mater Reliab 2008;8:561–4.
[43] Won Yeo Ji, Jik Lee Hyun, Jung Ha Soo, Lee Sang-Il, Gu Yeon-U, Kim Jong-Soo. Development of cooling system of LED headlamp for vehicle using vapor chamber type heat pipe. Proceedings of the 10th international heat pipe symposium 2011:48–53.
[44] Tsai M Y, Chen C H, Kang CS. Thermal analyses and measurements of low-cost COP package for high- power LED. IEEE 58th electronic components and technology conference 2008:1812–8.
[45] Wu Ming-hsiu. Integrated numerical and experimental study on thermal management of automobile LED lamps. ([Master thesis]). Taiwan: National Taiwan University of Science and Technology; 2011.
[46] Mentor. Thermal simulation and characterization optimizes LEDs for automotive applications; 2013. Available online ⟨http://www.mentor.com/pro ducts/mechanical/ resources/overview⟩.
[47] Kim Young-Woo, Kim Min-Sung, Park Sung-Mo, Kim Jae-Pil, Song Sang-Bin, Whang Nam, et al. Optimization of flexible substrate for automotive LED rear-lamp. IEEE 11th electronics packaging technology conference 2009:926–9.
[48] Wang Jing, Cai Yi-xi, Zhao Xin-jie, Zhang Chun. Thermal design and simulation of automotive headlamps using white LEDs. Microelectron J 2014;45:249–55.
[49] Long Xing-Ming, Liao Rui-Jin, Zhou Jing. Investigation on junction temperatures of multichip-on-board packaged light emitting diodes with configurable electrical power. J Light Visual Environ 2013;37:6–15.
[50] Long Xing-Ming, Liao Rui-Jin, Zhou Jing. Numerical simulation on electronic-thermal properties of gallium nitride based light emitting diodes embedded in board. Adv Optoelectron 2012:1–6.
[51] Jiao Jianghong, Wang Ben. High efficiency reflector optics for LED automotive forward lighting. SPIE proceedings of nonimaging optics and efficient illumination systems IV 2007;6670:1–10.
[52] Hsieh Chi-Chang, Li Yan-Huei, Huang CHih-Ching. Modular design of the LED vehicle projector headlamp system. Appl Opt 2013;52:5221–9.
[53] Ben Yanqing, Yang Hongqiao. Research on multi-LED headlamp lighting system adjustment mechanism design—based on Besturn B70 LED headlamp design. In: 2011 International conference on mechatronic science, electric engineering and computer; 2011. p. 684–686.
[54] Ge A, Du Z, Wang W, Qiu P, Wang J, Cai J, et al. A composite optical system for a LED based headlamp low beam module. Ligh Res Technol 2013;45:752–7.
[55] Florian R. Fournier. A review of beam shaping strategies for LED lighting. SPIE proceedings of illumination optics II 2011;8170:1–11.
[56] Chang Hsieh Chi, Huei Li Yan. Design of the light-emitting diode vehicle projector headlamp system without shield. Appl Mech Mater 2013;284-287:2723–8.
[57] Michenfelder Steffen. Automotive pixel lighting based on projectors. ATZ Worldwide 2013;115:60–4.
[58] Cvetkovic A, Dross O, Chaves J, Benitez P, Miñano JC, Mohedano R. Etendue-preserving mixing and projection optics for high-luminance LEDs, applied to automotive headlamps. Opt Express 2006;14:113014–20.
[59] S. Tarashioon, S Koh, W. van Driel, G. Zhang. Temperature dependency in performance of solid state lighting drivers. In:12th International conference on thermal, mechanical and multi-physics simulation and experiments in microelectronics and microsystems (EuroSimE); 2011. p. 1–3.
[60] Saponara S, Pasetti G, Costantino N, Tinfena F, D'Abramo P, Fanucci L. A flexible LED driver for automotive lighting applications: IC design and experimental characterization. IEEE Trans Power Electron 2012;27:1071–5.
[61] Zhao Chen, Xie Xiaogao, Liu Shirong. Multioutput LED drivers with precise passive current balancing. IEEE Trans Power Electron 2013;28:1438–48.
[62] Ying-yan Lin, Jing Zhang, Xue-cheng Zou, Wei Li. An efficiency-enhanced low dropout linear HB LED driver for automotive application. IEEE international conference on electron devices and solid-state circuits 2008:1–4.
[63] Gacio D, Calleja A J, Garcia J, Ribas J, Rico-Secades M. Suitable switching converter topologies for automotive signal lamps and headlamps using power LEDs. In: 2008 industry applications society annual meeting; 2008. p. 1–7.
[64] AN-1872. LM3423 Boost evaluation board. Available online ⟨http://www.ti.com/lit/ug/ snva354a.pdf⟩.
[65] T.W.Ching, T.H.Cheong. Review of dimming techniques for high-brightness LED. In: 26th IEEE Canadian conference of electrical and computer engineering; 2013. p. 1–4.
[66] Royo S, Arranz MJ, Arasa J, Cattoen M, Bosch T. New cost-effective sensor for the characterization of automotive headlamps by measurements in the near field. Sens. Actuators, A 2006;132:56–62.

[67] Chen Jinjia, Lin Pochun, Huang Kuanglung. Computer modeling of a fiber-and-light-emit ting-diode-based vehicle headlamp. Opt Eng 2010;49: 073002.1–3.8.

[68] Günther A. Optical concept for an active headlamp with a DMD Array. SPIE proceedings of optical sensors 2008;7003:1–8.

[69] Takai I, Ito S, Yasutomi K, et al. LED and CMOS image sensor based optical wireless communication system for automotive applications. IEEE Photonics J 2013;5:6801418.

[70] Wan Weibing, Fang Tao, Li Shuguang. Vehicle detection algorithm based on light pairing and tracking at nighttime. J Electron Imaging 2011;20:1–10.

[71] Ge Aiming, Wang Wei, Du Zhengqing, Qiu Peng, Wang Junwei. High-efficiency optical system for an LED—based headlamp architecture. Appl Opt 2013;52:8318–23.

[72] Chen Fei, Wang Kai, Qin Zong, Wu Dan, Luo Xiaobing, Liu Sheng. Design method of high-efficient LED headlamp lens. Opt Express 2010;18:20926–38.

[73] Whang AJW, Jhan KC, Chao SM, Chen GW, Chou C H, Lin C M, et al. An innovative vehicle headlamp design based on high-efficiency LED light pipe system. Light Res Technol 2013;0:1–11.

[74] Heng-Yi Haung, Shi-Mu Lin. Design of array LED automotive headlamp; 2012. Available online ⟨http://www.optics.ntut.edu.tw/files/15-1093-30747,c6948-1.php⟩.

[75] Jeff Perkins. LED manufacturing technologies and costs. DOE workshop [Report]. Yole Development; 2009.

[76] LED magazine. Available online ⟨http://ledsmagazine.com/features/10/3/4/1303 LED_SILf08⟩.

[77] Fujii Yoshie, Strijbosch Willem, Vogler Oliver, et al. Chain Lighting: charting the evolving automotive LED value chain [Report]. Mckinsey and Company, Inc; 2012; 1–9.

[78] McKinsey & company, Inc. Lighting the way: perspectives on the global lighting market [Report]. 2012. Available online ⟨http://www.mckinsey.com/~/media/McKinsey/dotcom/client_service/Automotive%20and%20Assembly/Lighting_the_way_Perspectives_on_global_lighting_market_2012.ashx⟩.

[79] Sousa J M M, Vogado J, Costa M, Bensler H, Freek C, Heath D. An experimental investigation of fluid flow and wall temperature distributions in an automotive headlight. Int J Heat Fluid Flow 2005;26:709–21.

[80] F Herrmann, K Trampert, C Neumann. LED-systems—colour shifts and colour presentation. In: Proc. of the Lux Europa, 12th European lighting conference; 2013. p. 1–5.

[81] Kettlitz M, Krylova O, Ehrlichmann D, Gunther K, Vollmer L. Color shift of head lamps for automotive lighting over lifetime. In: 41st IAS annual meeting; 2006. p. 1791–1793.

[82] Chambion B, Mendizabal L, Bechou L, Gasse A, Deshayes Y, Carreau V. Electro-optical strength assessment of white LEDs multichip modules for automotive forward-lighting application: failure analysis and packaging influence. IMAPS European microelectronics packaging conference 2013:1–7.

[83] U.S. Department of Energy. Lifetime and reliability [Report]; 2013, p. 4.

[84] Kang B, Yong B, Park K. Performance verifications of LED headlamps. Int J Automot Technol 2010;5:737–42.

[85] Long Xing-Ming, Liao Rui-Jin, Zhou Jing. Thermal uniformity of packaging light-emitting diodes arrays embedded on aluminum core printed circuit boards. Microelectron Reliab 2013;53:544–53.

[86] B Chambion. Electro-optical characterizations for robustness assessment of automotive qualified white LEDs multichip modules: failure analysis and packaging influence. In: 10th International symposium on automotive lighting; 2013. p. 23.

[87] Philips. LED driver lifetime and reliability [Report]; 2011.

[88] Kulkarni C, Celaya J, Goebel K, Biswas G. Prognostics health management and physics based failure models for electrolytic capacitors. Proceedings of American institute of aeronautics and astronautics 2012:1–8.

[89] Furkan Sokmen K, Pulat Erhan, Yamankaradeniz Nurettin, Coskun Salih. Thermal computations of temperature distribution and bulb heat transfer in an automobile headlamp. Heat Mass Transfer 2014;50:199–210.

[90] Bielecki J, Farmington Hills MI, Jwania A S, El Khatib F, Poorman T. Thermal considerations for LED components in an automotive lamp. In: IEEE semiconductor thermal measurement and management symposium 2007:37–43.

[91] Hui S Y, Qin YX. A general photo-electro-thermal theory for light emitting diode (LED) systems. IEEE Trans Power Electron 2009;24:554–62.

[92] IEEE Std. 802.15.7. IEEE Standard for local and metropolitan area networks-Part 15.7: short-range wireless optical communication using visible light, IEEE, Piscataway, N.J.; 2011.

[93] Seok-Ju Lee, Sung-Yoon Jung. A SNR analysis of the visible light channel environment for visible light communication. In: 18th Asica-Pacific conference on communications; 2012. p. 709–712.

[94] Nagura Toru, Yamazato Takaya, Katayama Masaaki, Yendo Tomohiro, Fujii Toshiaki, Okada Hiraku. Improved decoding methods of visible light communication system for ITS using LED array and high-speed camera. IEEE vehicular technology conference 2010:1–5.

[95] Transport Canada. Intelligent Transportation Systems; 2013. Available online ⟨http://www.tc.gc.ca/eng innovation/its-menu.htm⟩.

[96] Hwang Alex D, Peli Eli. Development of a headlight glare simulator for a driving simulator. Transp Res Part C 2013;32:129–43.

[97] National Highway traffic safety administration. Human factors; 2013. Available online ⟨http://www.nhtsa.gov/Research/Human+Factors/What+is+Human+Factors⟩.

[98] Y Kita. Color appearance of road signs under LED headlamps for drivers with different eye colors. In: 10th international symposium on automotive lighting; 2013. p 22.

[99] Sivak M, Schoettle B, Minoda T, Flannagan M J. Blue content of LED headlamps and discomfort glare [Technical Report]. University of Michigan Transportation Research Institute. USA 2005.